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(54) **Geosynchronous communications satellite system with reconfigurable service area**

(57) A geosynchronous, multi-beam phased array satellite system 20 transmits to and receives from the earth radio frequency signals. The satellite system 20 has transmit 28 and receive phased arrays 29, beamformers 26 and 27, switch matrices 24 and 25, a switch controller 23 and a communications payload 22. The beam coverage of the phased array satellite system 20 is reconfigurable while the satellite 20 is its geosynchronous orbit. The geosynchronous multi-beam phased-array satellite system 20 provides a more cost effective and weight effective way of providing communications for geosynchronous satellite applications.

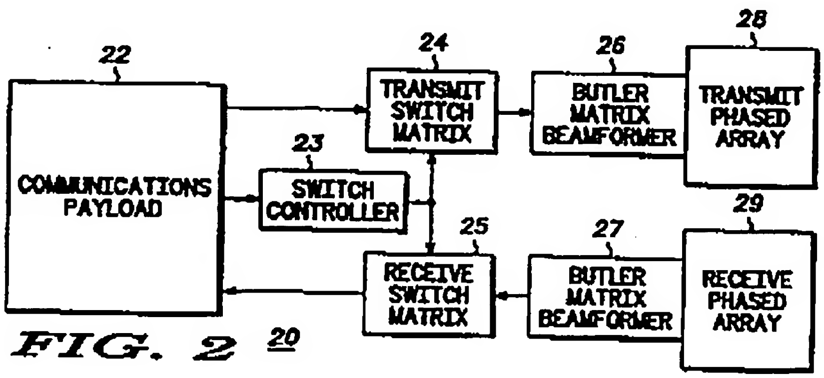

FIG. 2 20

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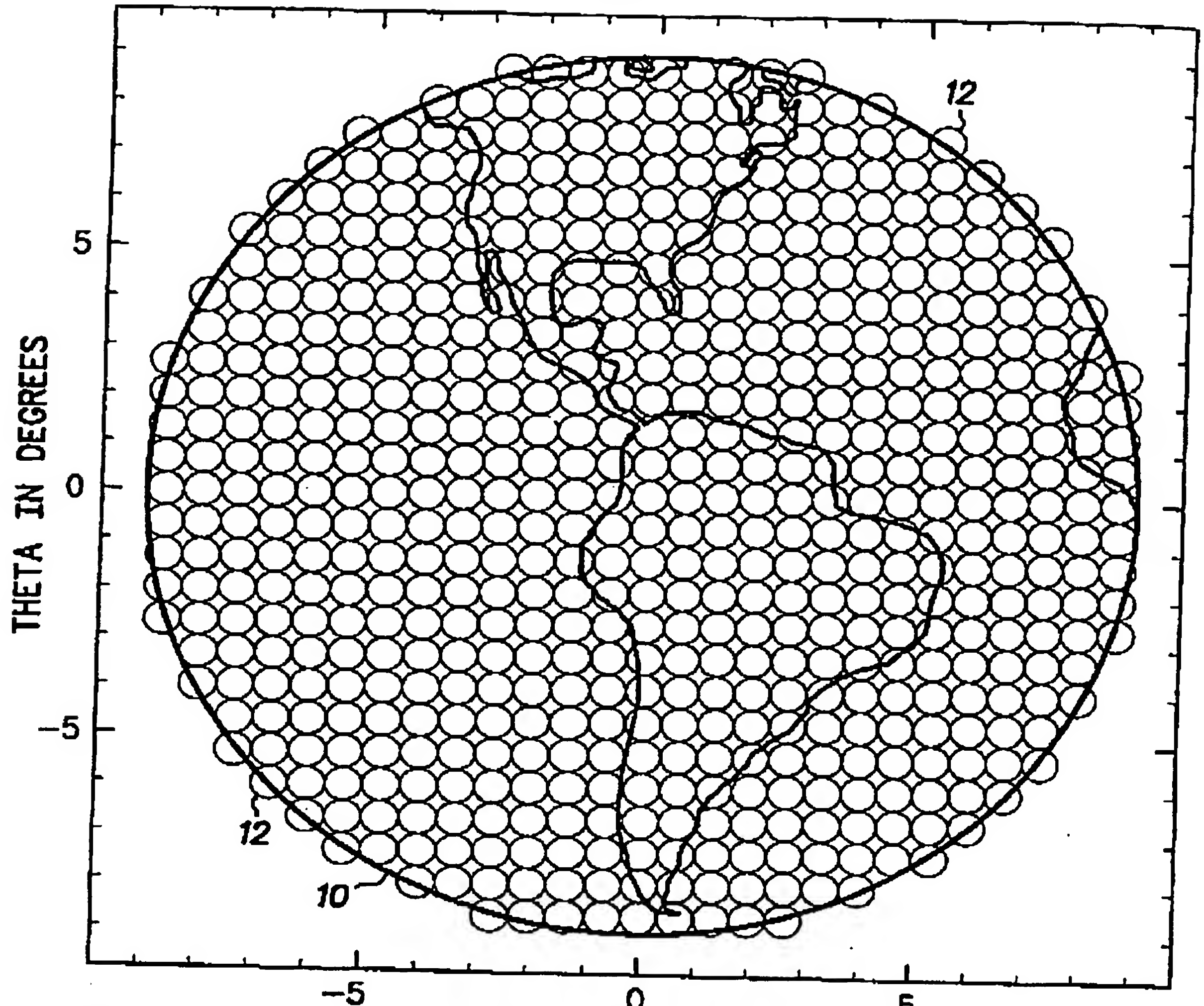

FIG. 1

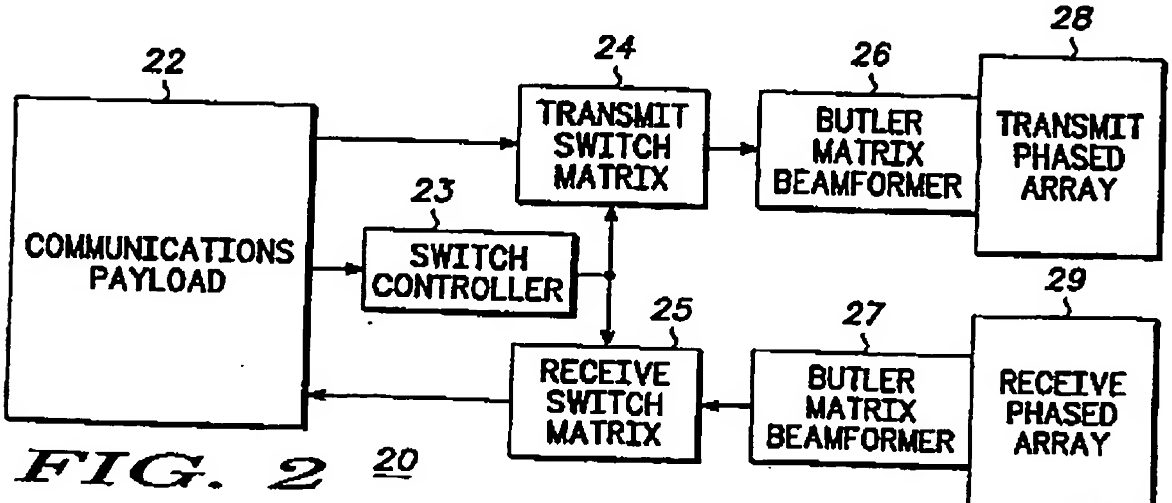

FIG. 2 20

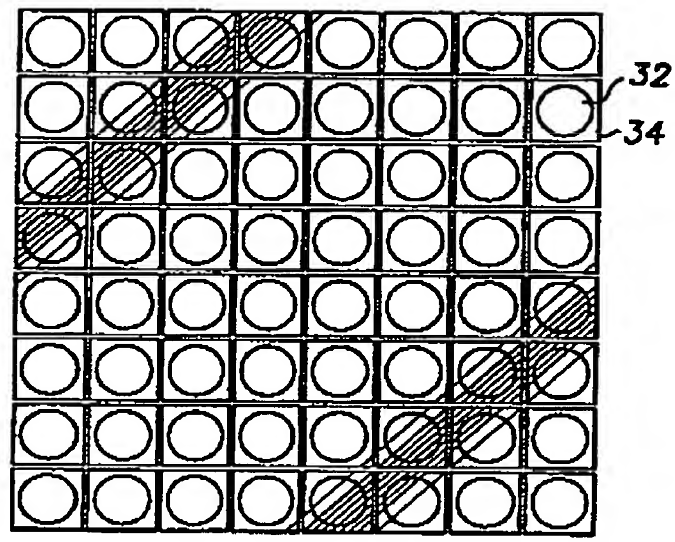

FIG. 3 30

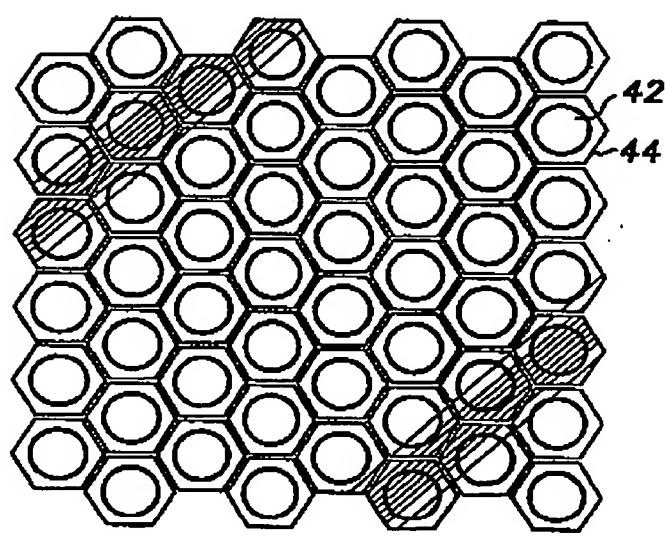

FIG. 4 40

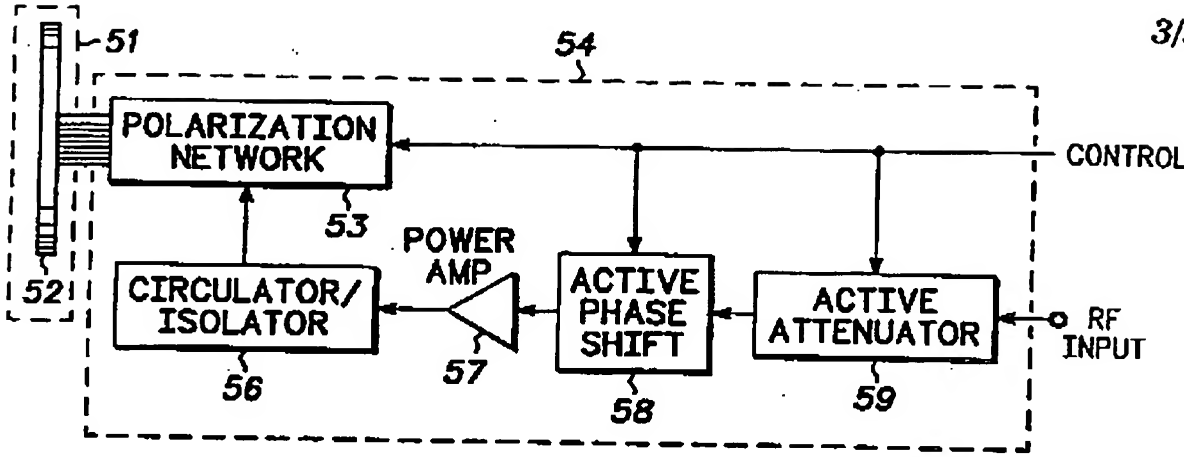

FIG. 5 50

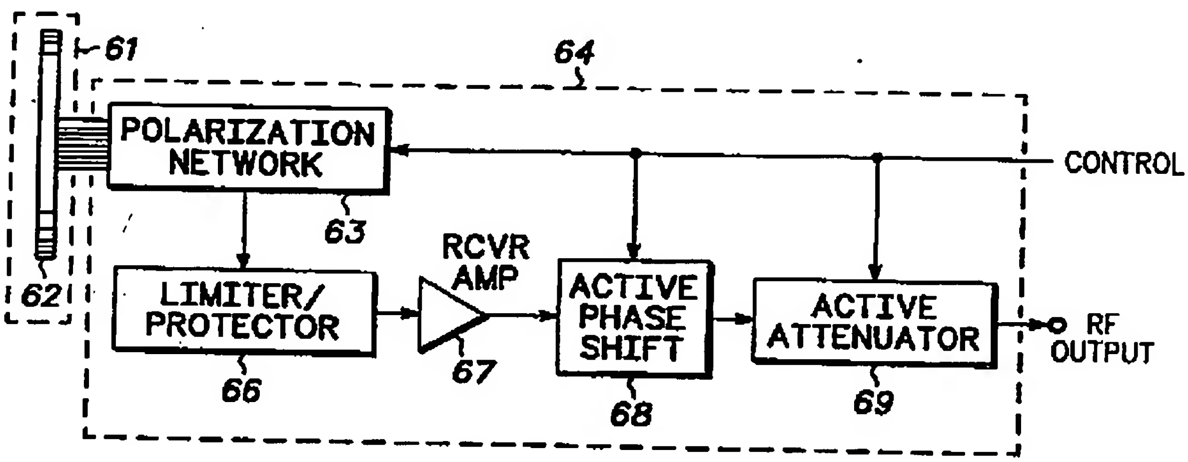

FIG. 6 60

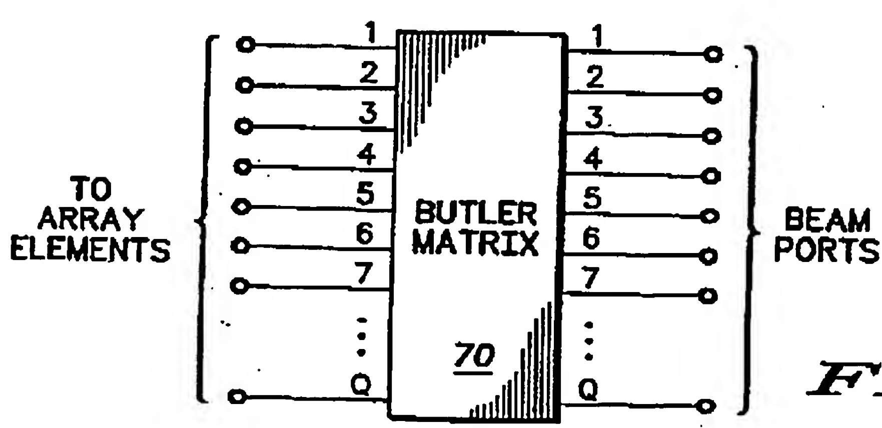

FIG. 7

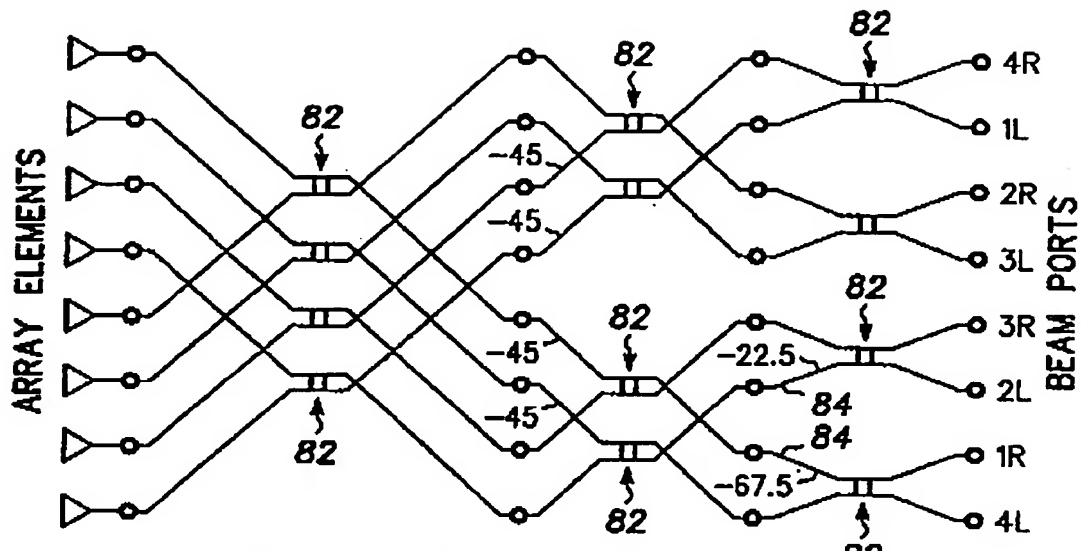

FIG. 8 70

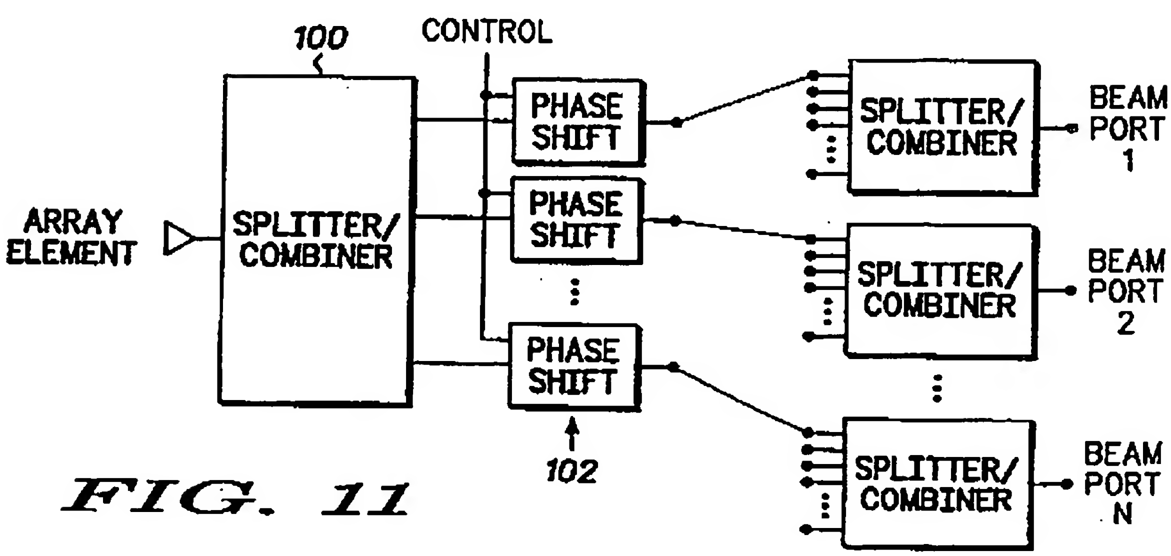

FIG. 11

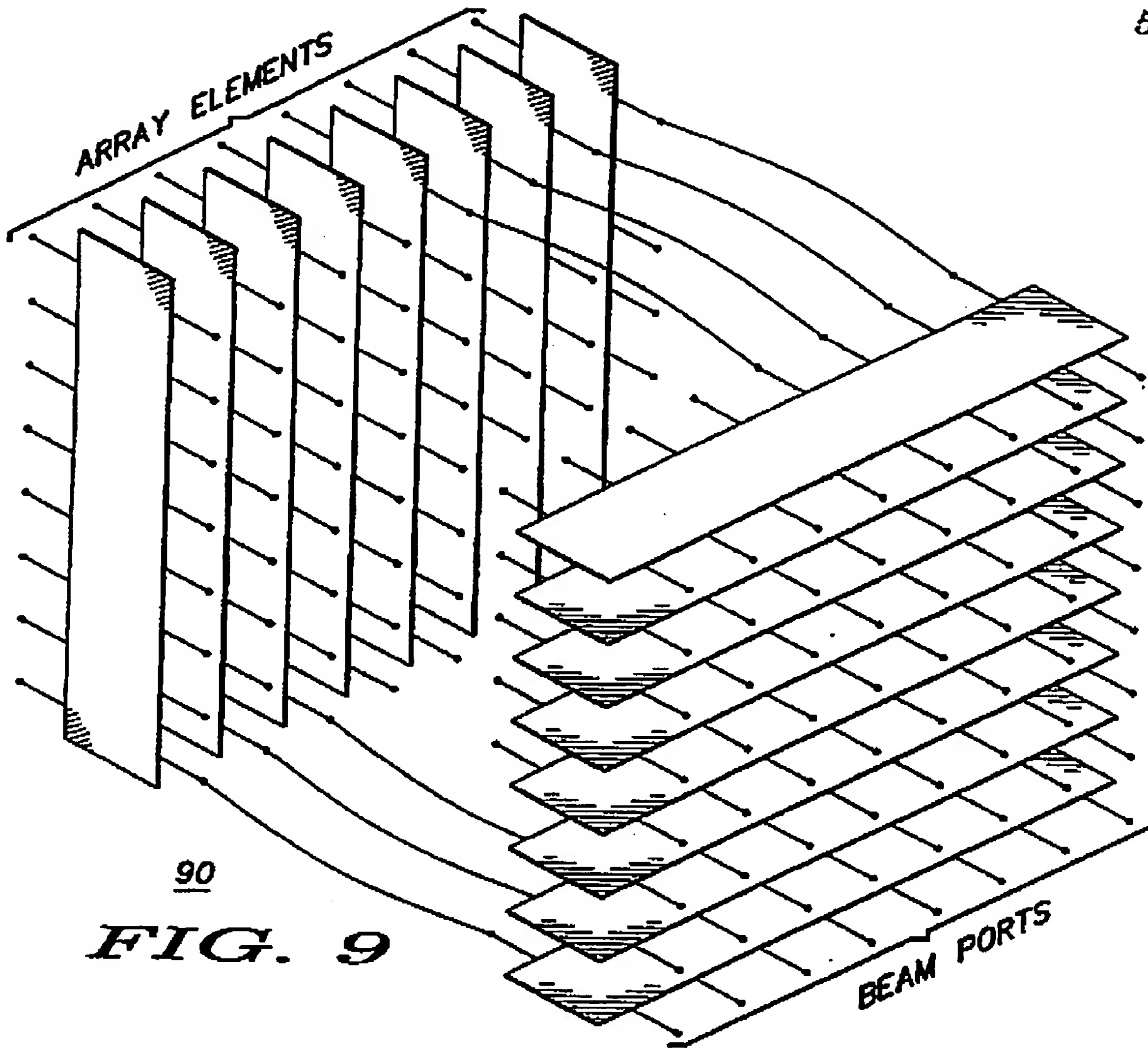

FIG. 9

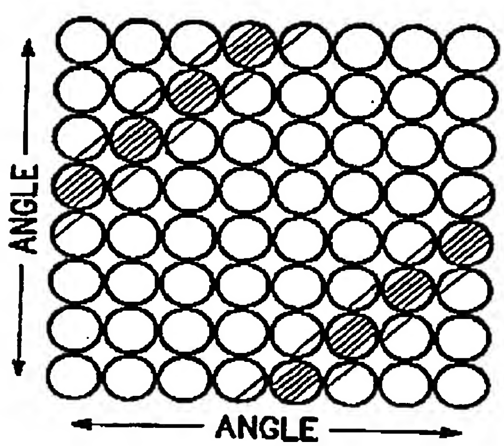

FIG. 10

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GEOSYNCHRONOUS COMMUNICATIONS SATELLITE SYSTEM WITH RECONFIGURABLE SERVICE AREA

Technical Field

This invention relates generally to satellite communications systems and, in particular, to a geosynchronous communications satellite system with a multi-beam phased array antenna capable of reconfiguring a service area.

Background of the Invention

All satellites in geosynchronous earth orbit (GSO) share two important characteristics. First, they remain approximately stationary relative to the earth's surface; and second, they have nearly an entire hemisphere within their radio field of view. The first of these characteristics, geostationary, is what gives GSO its name, and has been thoroughly exploited since the first satellites were placed in GSO. Exploitation of the hemispherical field of view, however, has been hampered by what could be achieved by practical antenna systems.

Conventional satellite communications systems use antennas which form each antenna beam with a dedicated feed structure. These feeds use passive microwave circuit technology (generally wave guide) and are therefore fairly large and heavy, at least by satellite standards where size and weight are a premium. Traditionally, GSO satellites were made to form a small number of beams to exploit its immense field of view. Each beam covered very large land masses, often approaching full continental coverage in a single beam. Since, by definition a large beam provides little antenna gain (i.e. directivity), these large beams required high power transmitters on the satellite and very large antennas on fixed earth stations. The earth terminal antennas ranged from 4 or 5 meters for Ka-Band up to tens of meters for lower frequencies.

The current trend in satellite communications is toward very small satellite earth terminals (VSAT) and ultra small satellite earth terminals (USAT). These terminals use small, and therefore, relatively low gain antennas. For practical reason (e.g., cost, safety, balanced up/down links), most of the lost earth terminal antenna gain cannot be compensated for with higher power transmitters. The satellite must compensate for the lost earth terminal gain by increasing the gain of

the satellite antenna, which of course reduces the area covered by each beam.

Conventional antenna techniques are limited by available size and weight to a maximum of about 100 beams, however much fewer beams is preferred. This is not only due to the size and weight of the antenna and feed structures, but also to the size, weight and power of the transmitter power amplifiers. In a conventional antenna system, each beam has a dedicated power amplifier and, in order to minimize the number of beams required, these amplifiers are operated at relatively high power. Traveling-wave-tube amplifiers (TWTA's) are typically used for these amplifiers in spite of their higher weight and lower reliability relative to solid-state amplifiers.

Ka-Band (i.e. 20 GHz downlink / 30 GHz uplink) requires approximately 500 to 1000 beams to cover an entire field of view from a GSO satellite, when the beams are sized to operate with low power earth terminals using sub-meter antennas. Since a practical conventional satellite antenna system can form about 100 beams, only about 10% of the field of view can be served. Thus, the market area that will be served must be predetermined and then the satellite antenna has to be custom designed according to the particular combination of orbital position ("slot") and service area. This approach carries at least four disadvantages. First, in a dynamic and uncertain market, there is the danger that the service location will be selected incorrectly, resulting in poor financial performance. Second, even if the area is initially correct, there is a danger that the market will evolve such that the area of service demand shifts away from the selected area before the useful life of the satellite is completed. Third, spares must be built for every orbital position and antenna combination (which is very expensive), or spares cannot be completed until a failure occurs (which results in prolonged service outages). Finally, design costs are increased and economies of scale are reduced because every satellite must be customized to its particular orbital slot / coverage area.

Accordingly, there is a significant need for a geosynchronous satellite system that is more cost effective and has lower weight for providing communications from geosynchronous orbit. Further, what is needed is a multiple-beam antenna that provides the ability to, while

in orbit, configure and reconfigure antenna coverage for particular regions on the earth.

Brief Description of the Drawings

FIG. 1 shows antenna beams of a satellite covering a portion of the earth within the field-of-view of the satellite.

FIG. 2 shows a block diagram of components of a satellite according to a preferred embodiment of the present invention.

FIG. 3 shows a small square grid section of the radiating face of the arrays.

FIG. 4 shows a small triangular grid section of the radiating face of the arrays.

FIG. 5 shows components of each active element of a transmit array.

FIG. 6 shows components of each active element of a receive array.

FIG. 7 shows a portion of an embodiment of a multiple-beam beamformer.

FIG. 8 shows a network of eight 8-element column beamformers and eight 8-element row beamformers.

FIG. 9 shows a network of eight 8-element column combiners and eight 8-element row combiners.

FIG. 10 shows an 8 by 8 set of contiguous beams which are formed by a network.

FIG. 11 shows a portion of a second embodiment of a multiple-beam beamformer.

Description of the Preferred Embodiments

The present invention has utility in that a geosynchronous satellite system avoids the disadvantages listed above by combining phased array technology with on-board switching and control. The satellite system comprises of a unique combination of three components: active transmit and receive phased array antennas with multiple beamformers (e.g., Butler matrices); beam selection switch matrices (one transmit, one receive); and a beam selection controller (commanded from the ground). Those skilled in the art understand that multi-beam beamformers may comprise any beamformer which forms multiple orthogonal beams, including for example, Butler

matrix beamformers (as described herein) and Rotman lens beamformers. In addition, the satellite includes a communications payload and a conventional satellite bus. The communications payload includes dynamic channel allocation capability so that capacity can be moved from one beam to another. This further enhances the capability of the satellite system to reconfigure the resources applied to the service area.

FIG. 1 shows antenna beams 12 of a satellite covering a portion of earth 10 within the field-of-view of the satellite. The antenna beams 12 are selectable while the satellite is in orbit, for active communications with earth-based terminals. The earth's disk 10 as seen from geosynchronous orbit is approximately +/- 8.7 degrees. Consequently, about 500 beams, each having 0.7 degrees beam width is required to fully cover the earth's disk as seen from a geosynchronous satellite. A geosynchronous satellite is a satellite orbiting the earth at a distance of 35860 kilometers and remains directly over an assigned spot on the earth's equator.

FIG. 2 shows a block diagram of components 22-29 of a geosynchronous satellite system 20 according to a preferred embodiment of the present invention. Components 22 -29 are just some of many components that comprise a satellite. For example, there are navigation components for positioning the satellite and power components for generating and maintaining power for the electronic components of satellite 20.

As shown in FIG. 2, satellite system 20 comprises communications payload 22, switch controller 23, transmit switch matrix 24, receive switch matrix 25, Butler matrix beamformer 26 and 27, transmit phased array 28 and receive phased array 29. Communications payload 22 receives L active beam signals to transmit switch matrix 24, and is responsible for selecting beam commands for switch controller 23. Switch controller 23 receives selected beam commands from communications payload 22 and selects N beam ports for orthogonal (e.g., a Butler matrix) beamformer 26 and 27. Transmit switch matrix 24 receives L active beam signals from N beam ports (selected by switch controller 23) from orthogonal (e.g., Butler matrix) beamformer 26 and transmit phased array 28. Receive matrix 25 receives signals from N beam ports (selected by switch controller 23)

from orthogonal beamformer 27 (e.g., Butler matrix) and transmits L active beams signals to communications payload 22.

Transmit phased array 28 and receive phased array 29 each comprises an array of a number of elements. Transmit phased array 28 is responsible for transmitting radio frequency (RF) signals, while receive phased array 29 is responsible for receiving RF signals from earth. The RF signals may be data or voice signals. A transmit multi-beam phased array 28 comprises an array of a number of active transmitting elements. A receive multi-beam phased array 29 comprises an array of a number of active receiving elements.

FIG. 3 shows individual antenna elements in a square grid 30. For a transmit phased array 28, the individual transmitting antenna elements 32 are used. For a received phased array 29 individual receiving elements are used. The transmit phased array 28 or receive phased array 29 can be positioned within an array aperture within the square grid 30 shown in FIG. 3 or in a triangular grid 40 as shown in FIG. 4.

FIG. 3 shows a small square grid section 30 of a face of an array, where the layout of the individual radiating elements in a square grid of columns and rows with each element 32 occupying a square section 34 of the total array area. FIG. 4 shows a small triangular grid section 40 of a transmitting face of an array, where the layout of the individual radiating elements in a triangular grid of columns and rows with each element occupying a hexagonal section of the total array area. (In FIGS. 3 and 4, only a 64 element sub-array 30, 40 of the total N-element array 22 is shown). The choice of an element grid depends on packaging, thermal management and angular field-of-view considerations, and is well understood by those skilled in the art.

In either array configuration 30 (FIG. 3) or 40 (FIG. 4), the directivity of the array aperture is defined as N times the directivity of a single array element 32 or 42, where N is the number of elements 32 or 42 and the single element directivity is $4\pi A_e/\lambda^2$. Here the element area 34 or 44, A_e, is the area of one individual square 34 in FIG. 3 or one individual hexagon 44 in FIG. 4. Lambda, λ, is the wavelength of the carrier frequency for which the array is designed (for example 20 GHz for a transmit array and 30 GHz for a receive array.

For generally circular array apertures, the angular width, at the -4 dB edge, of each of the beams formed by the array is approximately 67

λ/D degrees and the contiguous beams will be spaced on 57 λ/D degree centers. Since the transmission and reception are on different frequencies or wavelengths, the transmit and receive arrays must have different diameters in order that transmit/receive beam pairs have the same coverage.

FIG. 5 shows one of the individual transmitting elements 50 of transmit phased array 28 which comprises radiating element 51 and active transmit module 54. Radiating element 51 comprises passive radiator 52 which is coupled to a computer-controlled polarization network 53 located in active transmit module 54 that provides the ability to reconfigure beam polarization on-orbit. Radiating element 51 and polarization network 53 are commercially available from various vendors and are well known to those skilled in the art.

Transmit module 54 comprises computer-controlled polarization switching network 53, isolator 56, monolithic microwave integrated circuit (MMIC) linear power amplifier 57, computer-controlled phase shifter 58 and computer-controlled attenuator 59. As shown in FIG. 5, polarization network 53 is coupled to isolator 56 which is in turn coupled to solid state power amplifier 57. Amplifier 57 is coupled to active phase shifter 58 which is coupled to active attenuator 59. Attenuator 59 is coupled to the RF input. Phase shifter 58 and attenuator 59 (also MMIC's) are included to provide phase and amplitude control for compensation and calibration of each RF path through multi-beam phased array antenna. A computer located elsewhere on the geosynchronous satellite sends commands to driver circuits within components of network 53, phase shifter 58 and attenuator 59 to cause changes in polarization, phase or attenuation as determined necessary by on-board monitoring equipment. The components of active transmit module 54 are commercially available from Raytheon, Texas Instruments, et. al. and are well known to those skilled in the art.

FIG. 6 shows one of the individual receiving elements 60 of a receive phased array 29 which comprises receiving element 61 and active receive module 64. Receiving element 61 includes passive radiator 62 which is coupled to a computer-controlled polarization network 63 located in active receive module 64 which provides on-orbit reconfiguration of beam polarization. Receiving element 61 is

commercially available from various vendors and is well known to those skilled in the art.

Receive module 64 comprises computer-controlled polarization switching network 63, limiter/protector circuit 66 to protect against high interfering signals, MMIC low-noise receiver amplifier 67, computer-controlled phase shifter 68 and computer-controlled attenuator 69. As shown in FIG. 6, polarization network 63 is coupled to limiter/protector circuit 66 which is coupled to low-noise solid state receiver amplifier 67. Amplifier 67 is coupled to active phase shifter 68 which is coupled to active attenuator 69. Attenuator 69 is coupled to RF Output. Phase shifter 68 and attenuator 69 (also MMICs) are included to provide phase and amplitude control for compensation and calibration of each RF path through multi-beam phased array antenna. A computer located elsewhere on the geosynchronous satellite sends commands to driver circuits within components of network 63, phase shifter 68 and attenuator 69 to cause changes in polarization, phase or attenuation as determined necessary by on-board monitoring equipment. The components of active receive module 64 are commercially available from Raytheon, Texas Instruments, et. al. and are well known to those skilled in the art.

FIG. 7 shows a portion of one embodiment of multi-beam beamformer 26 or 27 (FIG. 2). As shown in FIG. 7, a portion of each beamformer 26 or 27 is a Butler matrix (which is well known to those skilled in the art) feed forming 8 beams with 8 radiating elements. The inputs to network 70 shown in FIG. 7 would be all of the outputs from the transmitting elements or receiving elements in one column of transmit phased array 28 or receive phased array 29 (FIG. 2). The beam available at each output beam port is a fan beam which is narrow in the dimension associated with the length of the column of elements and wide in the dimension associated with the width of a single element. The details of an 8-input example of network 70 is shown in FIG. 8. As shown in FIG. 8, each Butler matrix beamformer 26 or 27 comprises a number of hybrid couplers 82 and fixed phase shifters 84. The configuration of Butler matrix 70 shown in FIG. 8 is well known to those skilled in the art.

When network 70 of FIG. 7 is connected to each column of elements of an transmit phased array 28 or receive phased array 29 and a similar network is connected to each row of the column beam ports,

pencil beams are formed. The pencil beams are contiguous, touching each other at about the -4 dB points and, if transmit phased array 28 or receive phased array 29 was directed toward the earth, it would cover the portion of the earth as shown in FIG. 1.

A network 90 for combining a 64 element array of 8 columns and 8 rows is shown in FIG. 9. This network would form the 8 by 8 set of beams shown in FIG. 10.

An alternative to the beamforming implementation which forms all the beams needed to cover the earth and then selects M of those beams for activation is an implementation in which only M beams are formed, but each is individually steerable to any position on the earth's surface. The replacement for the beamforming network described in FIGS. 7, 8 and 9 is partially shown in FIG. 11. Here the active modules (FIGS. 5 and 6) of each element of transmit phased array 28 or receive phased array 29 are each followed by a 1-to-M splitter/combiner network 100, where M is the number of beams to be implemented. At each of the M outputs of splitter/combiner network 100 is computer-controlled phase shifter 102. One of the M phase shifters 102 from each of the N array elements is then connected to an N-to-1 combiner/splitter to form an individually steerable beam. Thus MxN phase shifters are required in this implementation.

In either implementation of the beamforming network, the microwave circuits are low power in nature and can be manufactured using very large scale integration techniques to minimize weight and cost. The overall cost of the solid-state multi-beam phased array communications antenna with low-power transmitter power amplifiers distributed across the face of the antenna will be less than that of the traditional horn-fed reflector and high-power TWTA transmitter approach. Further, the described invention will have lower weight and provide on-orbit beam reconfigurability.

One of the keys to satellite system 20 is that phased array 28 and 29 and Butler matrix 26 and 27 form a regular array of potential antenna beams that cover the entire hemispherical field of view of the satellite 20. The switch matrix 24 and 25 selects which of these beams will be active at a particular time. In this way a single satellite design can be used for all orbit slot / coverage area locations and the disadvantages listed above are all avoided.

Beams are switched and channels reallocated between beams whenever the service area for a satellite needs to change. This can occur for the following reasons : (1) Initial configuration on orbit; (2) change of the area served by a particular satellite in a given slot to, for example, to serve a new market; (3) scheduled daily changes to track peak market demand - this would primarily only be changes in channel allocation although for some systems (such as educational programming) complete beam changes could be made; (4) configuration of a spare when it is assigned to replace a failed satellite (note that the spare could be placed on orbit without knowing in which slot it will eventually be needed); (5) temporarily reconfiguring the service area of a satellite to replace coverage from a failed satellite; and (6) moving a satellite from one slot to another to change its service area.

It will be appreciated by those skilled in the art that the present invention provides a more cost effective means of providing communications for geosynchronous satellite applications. The phased-array on satellite 20 is more flexible than a horn-fed, dish antenna system.

In addition to the advantages listed above, the reconfigurability of system 20 provides a unique capability to dynamically allocate peaking capacity from GSO using multiple coverage of a service area from different slots. In this operational configuration, one satellite covers region "A" and a second satellite covers region "B" from the same or a different slot. A third satellite covers the busy parts of region "A" and the busy parts of region "B" from a different slot than the first two satellites. This "peaking" satellite could very dynamically reconfigure to serve the peak areas while the other satellites provide the basic coverage.

The GSO phased array satellite system 20 has at least two more advantages. First, the phased array is inherently more reliable than a TWTA approach due to its "soft failure" capability. Second, the phased array approach allows smaller beams which in turn require less transmitter power. This power savings is used to compensate for the lower efficiency of the phased array and to allow a larger payload and or more beams to be included in the design if necessary. The smaller beams also allow the earth terminal to use smaller antennas and lower

transmitter power which enhances the commercial viability of the system.

Accordingly, it is intended by the appended claims to cover all modifications of the invention which fall within the true spirit and scope of the invention.

Claims

What is claimed is:

1. A satellite system comprising:

an array of elements, where each element is capable of transmitting signals from the satellite in geosynchronous orbit;

a beamformer coupled to the array of elements;

a transmit switch matrix coupled to the beamformer via a plurality of beam ports; and

a switch controller coupled to the transmit switch matrix capable of selecting some of the beam ports.

2. The satellite system recited in claim 1, wherein each element of the array of elements occupies a square section in a square grid of one of a plurality of columns and rows.

3. The satellite system recited in claim 1, wherein each element of the array of elements occupies a hexagonal section in a triangular grid of one of plurality of columns and rows.

4. The satellite system recited in claim 1, wherein each elements in the array of elements comprises:

a radiating element; and

an active transmit module coupled to the radiating element.

5. The satellite system recited in claim 4, wherein the radiating element comprises a passive radiator.

6. The satellite system recited in claim 5, wherein the active transmit module comprises:

a polarization switching network that is capable of reconfiguring beam polarization while the satellite is in geosynchronous orbit;

isolator coupled to the polarization switching network;

linear power amplifier coupled to the isolator;

phase shifter coupled to the linear power amplifier; and

attenuator coupled to the phase shifter.

7. The satellite system recited in claim 1, wherein the beamformer comprises a Butler matrix.

8. The satellite system recited in claim 7, wherein the Butler matrix comprises:

a plurality of hybrid couplers; and

a plurality of phase shifters coupled to some of the hybrid couplers.

9. A satellite system comprising:

an array of elements, where each element is capable of receiving signals at the satellite system in geosynchronous orbit;

a beamformer coupled to the array of elements;

a receive switch matrix coupled to the beamformer via a plurality of beam ports; and

a switch controller coupled to the receive switch matrix capable of selecting some of the beam ports.

10. A satellite comprising:

a transmit phased array of transmitting elements, where each transmitting element is capable of transmitting signals from the satellite in geosynchronous orbit;

a receive phased array of receiving elements, where each receiving element is capable of receiving signals at the satellite in geosynchronous orbit; and

a switch controller coupled to the transmit phased array and the receive phased array and capable of selecting some of the transmitting elements and some of the receiving elements.

The Patent Office

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Application No: GB 9713722.8
Claims searched: 1 to 10

Examiner: Jared Stokes
Date of search: 5 September 1997

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): H1Q (QFA, QFE, QFF, QFH)
H4L (LDRR, LDRSX)

Int Cl (Ed.6): H01Q (3/24, 3/26)

Other: On-Line - WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A	GB 2 288 913 A	(IMSO) See abstract, figure 3	-
Y	US 5 457 456	(Ball Corp.) See column 6 line 29-column 7 line 51	1,3,4,9,10
Y	US 5 355 138	(France Tel.) See whole document	1,3,4,9,10

X Document indicating lack of novelty or inventive step
Y Document indicating lack of inventive step if combined with one or more other documents of same category.
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